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EFFECT OF CRACK DEPTH AND SPECIMEN WIDTH ON FRACTURE TOUGHNESS OF A CARBON STEEL IN THE DUCTILE-BRITTLE TRANSITION REGION

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Abstract-The effects of crack depth (a/W) and specimen width W on fracture toughness and ductile-brittle transition have been investigated using three-point bend specimens. Finite element analysis is employed to obtain the stress-strain fields ahead of the crack tip. The results show that both normalized crack depth (a/W) and specimen width (W) affect the fracture toughness and ductile-brittle fracture transition. The measured crack tip opening displacement (CTOD) decreases and ductile-brittle transition occurs with increasing crack depth (a/W) from 0.1 to 0.2 and 0.3. At a fixed a/W (0.2 or 0.3), all specimens fail by cleavage prior to ductile tearing when specimen width W increases from 25mm to 40 and 50mm. The lower bound fracture toughness is not sensitive to crack depth and specimen width. Finite element analysis shows that the opening stress in the remaining ligament is elevated with increasing crack depth or specimen width due to the increase of in-plane constraint. The average local cleavage stress is dependent on both crack depth and specimen width but its lower bound value is not sensitive to constraint level. No fixed distance can be found from the cleavage initiation site to the crack tip and this distance increases gradually with decreasing in-plane constraint.

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1. INTRODUCTION

Conventionally, deeply cracked three-point bend specimen ($0.45 < a/W < 0.55$) is recommended for fracture toughness measurement [1-2], where a is the precrack depth and W is the specimen width. However, shallow cracks exist in many practical engineering structures, especially welded structures. To correlate measured toughness values for shallow crack specimens with structural behavior, the effects of crack depth on the fracture characteristics of the test specimen must first be understood. The influence of normalized crack depth (a/W) on fracture toughness has already been investigated [3-9]. The slip-line field analysis of Matsoukas, Cotterell and Mai [10] showed that the hydrostatic stresses are larger for deeper cracks. A number of finite element analyses [8-9, 11] also showed that the normalized crack depth (a/W) has a significant effect on the stress triaxiality ahead of the crack tip. For above circumstances, the relationship between the scaling parameters (stress intensity factor or J -integral) and the near crack-tip fields loses the one-to-one correspondence. The loss of uniqueness, often termed as loss of constraint, leads to a variation of fracture toughness with specimen geometry and crack depth. Therefore, constraint is a structural feature that inhibits plastic flow and causes high stress triaxiality. The study on the effects of constraint in fracture has turned out to be a general topic of active fracture mechanics research in recent years.

For low and medium carbon steels, ductile-brittle fracture transition has been frequently observed [12-13], where unstable fracture occurs by transgranular cleavage after a small amount of ductile crack growth. Ductile-brittle transition can also occur as a result of a transition from plane stress fracture for a thin plate to

plane strain fracture for a thick plate in which the high hydrostatic stress elevates the opening stress ahead of the crack tip. In the work of Wu et al. [5], notched-bend specimen of a medium carbon steel exhibits a ductile-brittle transition with increasing normalized crack length (a/W) due to the increase of in-plane constraint.

Usually, a/W is employed as a correlation parameter in the study of crack depth on fracture toughness. However, little work has been done on the effect of specimen width W on the toughness and the ductile-brittle transition. In the present study, the effects of both a/W and W on ductile-brittle transition have been investigated experimentally using three-point bend specimens for a carbon steel. Finite element analysis is carried out to obtain the stress-strain distributions ahead of the crack tip. The effects of constraint on fracture toughness and micromechanism of ductile-brittle transition are also studied.

2. EXPERIMENTAL PROCEDURE

The test material was hot-rolling CS1020 plain carbon steel whose chemical composition is given in Table 1. The yield strength $\sigma_0=630\text{MPa}$ and hardening exponent $n=0.05$ were obtained from round bar tensile specimens. The true stress-true strain relation is shown in Fig. 1. Three-point bend specimens with a/W ratio 0.1, 0.2 and 0.3 were machined from a 25 mm thickness steel plate. In order to investigate the effect of specimen width, some specimens were machined with an identical a/W but a different W . The dimensions of all specimens are listed in Table 2. It is sometimes very difficult to obtain straight fatigue precracks for shallow crack specimens. In this work, over-sized specimens (140% W) were first machined to promote a straight fatigue crack. Following fatigue pre-cracking, the

specimens were remachined to the W desired. Crack tip opening displacement (CTOD) at unstable fracture (δ_c) was obtained according to ASTM Standard E1290-93 [2]; then δ_c was corrected for crack growth using Hellmann and Schwalbe's equation [14], i.e.,

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_o E} + \frac{[r_p(W-a)+\Delta a]V_p}{[r_p(W-a)+a+Z]} \quad (1)$$

where K is nominal stress-intensity factor, E is Young's modulus, ν is Poisson's ratio, V_p is plastic component of the crack-mouth opening displacement at the unstable point on the load-displacement record, Z is distance of knife edge measurement point from the front face of specimen and r_p is the plastic rotation factor which was obtained from the correction given by Wu, Mai and Cotterell for shallow crack specimens [15-16]. CTOD at ductile initiation, $\delta_{0.2}$, was obtained by the multi-specimen resistance curve (δ_R -curve) method using TF specimens ($a/W=0.1$, $W=25\text{mm}$).

All tests were carried out at 25°C with a crosshead speed of 1.0 mm/min . The fracture surfaces of some specimens were observed with a scanning electron microscope (SEM).

3. FINITE ELEMENT ANALYSIS PROCEDURE

Two-dimension large deformation finite element analysis was carried out using ABAQUS code [17] under plane strain condition. Incremental plasticity theory was used for the material constitutive model. According to the specimen

dimensions shown in Table 2, different finite element meshes were generated for different specimens. Fig. 2 shows the details of the mesh near to the initial crack tip. About 1500 elements were used for each model. The initial crack tip width was 5 μ m. J -integral was evaluated according to the domain integral method. The integral contours were taken through the centroids of rings of elements far from the crack tip, Fig. 2.

4. RESULTS AND DISCUSSION

4.1 Critical CTOD values

For TE ($a/W=0.2$, $W=50$ mm) and TD ($a/W=0.3$, $W=40$ mm) specimens, fracture occurred as complete cleavage for all specimens without any ductile crack growth. That is the specimens fractured in the lower-shelf region. For TC ($a/W=0.2$, $W=25$ mm) and TB ($a/W=0.3$, $W=25$ mm) specimens, some specimens fractured without ductile growth, but for others cleavage was preceded by ductile crack growth. In contrast, for TF ($a/W=0.1$, $W=25$ mm) specimens, fracture in all cases showed a fully ductile mode, denoting upper-shelf behavior. Fig. 3 shows the critical CTOD (δ_c) at unstable fracture for TE, TD, TC and TB specimens. For TF specimens, six specimens were used to obtain the CTOD resistance curve. The CTOD corresponding to ductile growth $\Delta a=0.2$ mm was taken as the ductile initiation toughness ($\delta_{0.2}$). This value is also included in Fig. 3. A large scatter can be observed in this figure, especially for TB and TC specimens. This is a general feature in the ductile-brittle transition region and is expected. In order to compare the δ_c values for the different specimens, a statistical treatment is necessary.

Weibulls theory [18] has been widely used to analyze the size effect on failure in solids and assess structural reliability. Based on this theory a number of statistical models have been established to describe the data scatter for complete cleavage fracture [19-23]. Also, Weibulls theory has been used in the ductile-brittle transition region after some ductile crack growth [24-25]. The two-parameter Weibull equation in terms of δ can be expressed as

$$P_f = 1 - \exp\left(-\left\{\frac{\delta}{\delta_o}\right\}^{m_l}\right) \quad (2)$$

where P_f is fracture probability, m_l and δ_o are shape and scale parameters, respectively. P_f can be estimated in terms of

$$P_f = i - 0.5/n \quad (3)$$

where i is the order of the data point and n is the number of data points. Fig. 4 (a) shows the Weibull analysis for TC and TE specimens. It can be seen that TC specimens have higher toughness compared to TE specimens at the same fracture probability. Because both TE and TC have the same normalized crack depth $a/W=0.2$, the difference in toughness can only be attributed to the specimen width W (i.e., 50mm versus 25mm). Similar results are found for TB and TD specimens, as shown in Fig. 4(b). Therefore, at a fixed value of a/W , specimens with a larger W give a lower CTOD value. Smaller specimens undergo much more extensive plastic displacement before final fracture and result in a higher fracture toughness. The δ value corresponding to 63% fracture probability is shown in Table 3, where the initiation toughness $\delta_{0.2}$ for TF specimen is also included. It can be seen that the average CTOD increases in the order of TD, TE, TB and TC. The ductile initiation CTOD ($\delta_{0.2}$) of TF specimens is significantly greater than the value of δ_c

for all other specimens. For the specimens with an identical W , toughness decreases with increasing normalized crack depth a/W (TF, TC and TB specimens). Both TD and TE have the same average toughness (at 63% fracture probability). This is due to the similar constraint condition ahead of crack tip in both the TD and TE specimens, as illustrated later in the finite element analysis. It may be noted in Fig. 3 that the lower bound toughness of all specimens is not sensitive to the normalized (a/W) or specimen width (W). Zerbst, Heerens and Schwalbe [26] employed six different procedures to examine the lower bound toughness in the ductile-brittle transition region. They have found that the lower bound toughness corresponding to 5% fracture probability is basically independent of specimen geometry. Similar results were also found in other studies [23, 27]. The possible reason is that lower bound values of δ_c were achieved under conditions of well contained crack-tip plasticity where constraint effects are negligible.

4.2 Results of finite element analysis

To explain the variation of toughness measured in specimens with different crack depth and specimen width, an understanding of the crack tip stress field is essential. Fig. 5 shows the opening stress (σ_{yy}) distributions ahead of the crack tip. In Fig. 5, a dimensionless distance X/δ was used, where δ is 0.24mm for all the specimens. It is clear that both a/W and W affect the magnitude of the opening stress. For the specimens with an identical W but different a/W (TF, TC and TB), the opening stress is elevated with increasing a/W value from 0.1 to 0.3. This has been verified before by slip-line and finite element analysis [8-11]. The reason for the specimen with small a/W having a lower opening stress is due to the extensive plastic deformation ahead of crack tip which releases the in-plane constraint [8,

12]. Fig. 6 gives the distributions of stress triaxiality along the ligament. Stress triaxiality is expressed as the ratio of hydrostatic stress to equivalent stress (σ_m/σ_e). Fig. 7 gives the yielded zone (contour of $\sigma_e/\sigma_o=1$) for all specimens loaded to the same CTOD (0.25mm). Except TF specimen, the plastic zone is confined to the ligament, as shown in Fig. 7. Although both TC and TE have an identical crack depth $a/W=0.2$, the TC specimen has a significantly larger yielded zone compared to the TE specimen at the same CTOD level. This results in a decrease of the opening stress in TC specimen due to the release of constraint. For TF specimen, the plastic zone is much larger than other specimens at the same CTOD level. Also, the yielded zone has spread to the free surface behind the crack tip, Fig. 7(c). As a result, high opening stress cannot be developed in the ligament for TF specimen due to the extensive plastic yielding. This phenomenon was also observed in the work of Sorem et al [8]. For all specimens, the achievable opening stress ahead of the crack tip increases with increasing constraint (stress triaxiality) in the order of TF, TC, TB, TE and TD. This is consistent with the decrease of the average toughness as obtained in Table 3. Therefore, when correlating crack depth with fracture toughness, both normalized a/W and specimen width W should be considered simultaneously rather than only a/W .

Both J -integral and CTOD (δ) have been widely used as characterizing parameters in toughness testing and fracture mechanics assessment. A general relationship has been developed to relate the two parameters:

$$J = m\sigma_o\delta \quad (4)$$

where m is a constant. In the work of Anderson [28], m was proposed as an indicator of global constraint. In the work of Shih [29], he found that m is strongly

dependent on the hardening exponent but weakly dependent on the specimen geometry for bend type specimens. In this study, the J -integral was estimated using the domain integral method. The far field integral path is shown in Fig. 2. The CTOD was defined as the separation between the intercept of two 45° lines drawn back from the crack tip. The relationship between J -integral and CTOD is shown in Fig. 8. There is a small variation of m for TE, TD, TC and TB specimens. m increases mildly with constraint level. Therefore, m is not very sensitive to the constraint for the bend specimens with different crack depth.

4.3 Constraint and ductile-brittle transition

As discussed by Ritchie, Knott and Rice [30], the cleavage criterion was postulated as the opening stress exceeding the cleavage stress over a characteristic distance. Initially, the characteristic distance was assumed as two grain diameters. But in subsequent studies Curry and Knott [31-32] and Chen et al [33-35] found that no simple relationship existed between grain size and characteristic distance. The latter can be identified as a statistical distance needed to sample an eligible brittle particle. In Fig. 5, the position of peak opening stress is evaluated at about 1.5~2 times CTOD, i.e., $X/\delta=1.5\sim 2$. This means that with increasing applied load (δ) the absolute position of the peak opening stress moves away from the crack tip and the area covered by the opening stress increases. From the finite element analysis for a growing crack [11, 25, 36], the magnitude of the opening stress is elevated and the area covered by the opening stress increases with applied load after ductile crack growth. The probability of finding an eligible brittle particle is hence enhanced with increasing load and ductile crack growth. Conventionally, the maximum opening stress corresponding to the fracture load is taken as the

cleavage stress. However, cleavage initiation does not necessarily start at the site of the maximum opening stress [33-35, 37]. For the specimens without ductile crack propagation, from the calculated stress distribution corresponding to the fracture load, the opening stress at the initiation site could be determined and was taken as the local stress needed to initiate cleavage fracture, i.e., σ_f , as described in [33-35]. Table 4 shows the distance from the cleavage initiation site to the blunt crack tip (X_f) and the local cleavage stress σ_f . No fixed distance X_f can be found from the observation of fracture surface and there is a large scatter of X_f due to the random distribution of brittle particles. In Table 4 there is a scatter of σ_f measured in each type of specimens. This represents the inhomogeneity of the brittle particles, i.e., the size distribution of the brittle particles able to trigger cleavage fracture. On average, σ_f measured in TD and TE specimens are greater than that measured in TC specimens, as shown in Fig. 9. P is the rank probability. This means that the brittle particle with a higher strength, e.g., smaller sized particles, can be sampled by the elevated opening stress ahead of crack tip due to the increase of constraint. Thus, specimens with high constraint can sample more brittle particles compared to those with low constraint, thereby having a higher probability of cleavage fracture. However, the lower bound $\sigma_{f(min)}$ values (about 1470~1570MPa) is similar for different specimens. This lower bound strength is related to the weakest brittle particle. Therefore, while the average local cleavage stress is related to the constraint level, the lower bound value only depends on the strength of the weakest particles in the material. The statistical distribution of cleavage initiation distance from the crack tip (X_f) is shown in Fig. 10. It can be seen that X_f for TE and TD specimens are smaller than that for TC specimens.

That is, the cleavage initiation site from the crack tip increases with decreasing in-plane constraint. This is due to the peak opening stress moving away from the crack tip with loading. In previous work [38-39], a fixed characteristic cleavage distance has been assumed to predict the toughness variation in different specimen geometry. This is not accurate because the distance from the cleavage site to the crack tip depends on both the random distribution of brittle particles and the in-plane constraint.

For TD and TE specimens fracture occurs in complete cleavage due to the high opening stress. Compared to TE and TD specimens, some TC and TB specimens cleavage after some ductile crack growth due to the lower constraint level. On the other hand, the achievable opening stress ahead of the crack tip in TF specimen is lower than the lower bound value of the local cleavage stress, as shown in Fig. 5. Consequently, fracture in TF specimen is dominated by ductile tearing. Hence both a/W and W affect the achievable opening stress ahead of the crack tip and influence the ductile-brittle fracture transition.

5. CONCLUSIONS

The effects of crack depth (a/W) and specimen width W on fracture toughness and ductile-brittle fracture transition have been investigated using three-point bend specimens. Finite element analysis was used to obtain the crack tip stress-strain fields. Experimental and numerical analyses support the following conclusions:

1. Both normalized crack depth (a/W) and specimen width (W) affect the fracture toughness and ductile-brittle fracture transition. For a fixed specimen width ($W=25\text{mm}$), toughness decreases and ductile-brittle transition occurs with

increasing crack depth a/W from 0.1 to 0.2 or 0.3. At a fixed a/W (0.2 and 0.3), toughness decreases and all specimens fail by cleavage prior to ductile tearing with increasing W from 25 to 40 and 50mm. The lower bound fracture toughness is not sensitive to the crack depth (a/W) and specimen width (W).

2. At a fixed W , finite element analysis shows that the opening stress in the remaining ligament is elevated with increasing a/W . The extent of plastic deformation is significantly different for specimens with different a/W at the same CTOD. For specimens with shallow crack depth ($a/W=0.1$), the plasticity spreads to the free surface behind the crack tip. Also, at a fixed a/W , the opening stress increases with increasing specimen width W .
3. The average value of local cleavage stress is dependent on both crack depth and specimen width but its lower bound value is not sensitive to constraint level. No fixed distance can be found from the cleavage initiation site to the crack tip. This distance increases gradually with decreasing in-plane constraint. The possibility of ductile-brittle fracture transition can be estimated by comparing the achievable opening stress in the ligament with the lower bound value of cleavage fracture stress.

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Table 1 Composition of the materials (%)

C	Mn	S(max)	P(max)
0.25	0.90	0.06	0.06

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Table 2 Dimensions of three-point bend specimens

Specimen	a , mm	W , mm	a/W	B , mm
TF	2.5	25	0.1	25
TC	5.0	25	0.2	25
TB	7.5	25	0.3	25
TE	10	50	0.2	25
TD	12	40	0.3	25

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Table 3 CTOD corresponding to 63% fracture probability

	TD ($a/W=0.3$, $W=40\text{mm}$)	TE ($a/W=0.2$, $W=50\text{mm}$)	TB ($a/W=0.3$, $W=25\text{mm}$)	TC ($a/W=0.2$, $W=25\text{mm}$)	TF ($\delta_{0.2}$) ($a/W=0.1$, $W=25\text{mm}$)
δ_c , mm	0.042	0.042	0.11	0.19	0.35

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Table 4 Distance from cleavage site to crack tip (X_f)
and cleavage stress (σ_f)

Specimens	X_f , μm	σ_f , MPa
TC	300	1531
	337	1516
	363	1483
TD	113	1782
	209	1697
	261	1727
	290	1571
TE	131	1537
	181	1748
	275	1707
	293	1465

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CAPTIONS OF FIGURES

Fig. 1 True stress-strain relationship for the CS1020 steel

Fig. 2 Refined mesh for crack tip.

Fig. 3 CTOD (δ) measured in different specimens

Fig. 4 Weibull distribution of δ_c for (a) TC & TE specimens, and (b) TB & TD specimens.

Fig. 5 Distributions of opening stress ahead of crack tip for various specimens.

Fig. 6 Distributions of stress triaxiality ahead of crack tip for various specimens.

Fig. 7 Distributions of plastic zone (shaded area) ahead of crack tip for (a) TB, (b) TC, (c) TF, (d) TD, and (e) TE specimens.

Fig. 8 Relationship between CTOD and J -integral.

Fig. 9 Distribution of local cleavage stress for TC, TE and TD specimens.

Fig. 10 Distribution of distance from cleavage initiation site to crack tip for TC, TE and TD specimens.

